

Magnetic Diagnostics of the Solar Chromosphere with the Mg II h–k Lines

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ABSTRACT

We investigated the formation of the Mg II h–k doublet in a weakly magnetized atmosphere (20–100 G) using a newly developed numerical code for polarized RT in a plane-parallel geometry, which implements a recent formulation of partially coherent scattering by polarized multi-term atoms in arbitrary magnetic field regimes. Our results confirm the importance of partial redistribution effects in the formation of the Mg II h and k lines, as pointed out by previous work in the non-magnetic case. We show that the presence of a magnetic field can produce measurable modifications of the broadband linear polarization even for relatively small field strengths (~ 10 G), while the circular polarization remains well represented by the classical magnetograph formula. Both these results open an important new window for the weak-field diagnostics of the upper solar atmosphere.

1. Introduction

One of the big challenges faced these days by the solar physics community is to gain a solid understanding of the solar chromosphere, and how it magnetically connects to the underlying photosphere and the corona above.

Within the chromosphere, the structure and dynamics of the magnetized plasma undergo dramatic changes. This region spans approximately nine pressure scale heights, and the gas temperature goes through a minimum of only a few thousand K, before suddenly rising to the million K temperatures of the solar corona. As the gas density decreases, the intrinsic three-dimensional distribution of the solar radiation becomes increasingly important, because the excitation of the chromospheric ions becomes more strongly correlated with the degree of anisotropy of the radiation. At the same time, the reduced role of particle collisions in thermalizing the atomic populations allows for subtle quantum effects (e.g., atomic polarization, level-crossing coherence, the magnetic

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and electric Hanle effects in the presence of deterministic as well as turbulent fields) to become apparent in the spectral and polarization signatures of the solar chromosphere (Trujillo Bueno 2001; Landi Degl’Innocenti & Landolfi 2004; Casini & Landi Degl’Innocenti 2008).

Another increasingly important aspect of the modeling of chromospheric spectral lines in realistic solar scenarios is the ability to account for the higher temporal coherence between the processes of absorption and re-emission of the solar radiation, which is fostered by the particular physical state of the tenuous chromospheric plasma. This condition of *partially coherent scattering* gives rise to a plethora of phenomena (commonly dubbed *partial frequency redistribution* or PRD), which must be taken into account for a proper diagnosis of the plasma and magnetic properties of the chromosphere. In particular, PRD effects are fundamental for the interpretation of many quantum interference patterns that are observed in the solar spectrum even between widely separated multiplet lines. This was originally demonstrated by Stenflo (1980) in the case of the Ca II H–K doublet around 395 nm. Such effects are thus essential also for the modeling of the linear polarization of the Mg II h–k doublet around 280 nm (Auer, Rees, & Stenflo 1980; Henze & Stenflo 1987; Belluzzi & Trujillo Bueno 2012), which has a quantum structure similar to that of the Ca II H and K lines. Recently, polarized radiative transfer (RT) with PRD in the non-magnetic case has been applied to the modeling of a variety of chromospheric line multiplets showing quantum interferences (Smitha et al. 2012; Belluzzi & Trujillo Bueno 2014), as well as in the case of a uniformly magnetized slab (Smitha et al. 2013).

Independently, Casini et al. (2014; see also Casini & Manso Sainz 2016) have attacked the problem of the formation of spectral line polarization by partially coherent scattering in a magnetized medium, with sufficient generality to enable the modeling of many resonance lines of the solar spectrum that show complex linear polarization patterns (Wiehr 1975; Stenflo & Keller 1996, 1997; Stenflo, Keller, & Gandorfer 2000; Gandorfer 2000). In particular, that formalism allows to fully take into account the role of atomic polarization in the lower state of an atomic transition, a feature that has been neglected by previous works in PRD modeling. On the other hand, lower-level polarization is important for the interpretation of many chromospheric diagnostics, as demonstrated by Manso Sainz & Trujillo Bueno (2003) in the case of the Ca II IR triplet.

In order to apply the formalism of Casini et al. (2014) under realistic chromospheric conditions, we have developed a 1-D RT code for the polarized multi-term atom in an arbitrary magnetic field, which takes into account the effects of PRD, as well as the contribution of (isotropic) inelastic and elastic collisions. The code is based on a straightforward Λ -iteration scheme (e.g., Mihalas 1978), and it arrives at the solution for the polarized PRD transfer problem in a magnetized atmosphere in two steps. In the first stage we assume *complete frequency redistribution* (CRD), and solve the non-LTE problem of the second kind (Landi Degl’Innocenti & Landolfi 2004) for zero magnetic field and including only inelastic collisions. In order to facilitate the convergence of the CRD problem, we initialize the level populations with the non-LTE solution from the RH code (Uitenbroek 2001). In the second stage, this converged CRD solution is used to initialize the iteration for the magnetized PRD problem, with the further addition of elastic collisions. The effects of collisions are taken into

account in the RT equation by implementing physically consistent branching ratios between the first-order (CRD) and second-order (PRD) emissivity terms of the theory (cf. Casini et al. 2014). As a result, the emissivity term in the RT equation takes the form

$$\varepsilon_i(\omega_k, \hat{\mathbf{k}}) = \left[\varepsilon_i^{(1)}(\omega_k, \hat{\mathbf{k}}) - \varepsilon_i^{(2)}(\omega_k, \hat{\mathbf{k}})_{\text{f.s.}} \right] + \varepsilon_i^{(2)}(\omega_k, \hat{\mathbf{k}}) \quad (1)$$

where $\varepsilon_i^{(2)}(\omega_k, \hat{\mathbf{k}})_{\text{f.s.}}$ corresponds to the expression of $\varepsilon_i^{(2)}(\omega_k, \hat{\mathbf{k}})$ in the limit of flat-spectrum (f.s.) illumination. Using equation (15) of Casini et al. (2014), it is straightforward to verify that the emissivity (1) converges to the one of Uitenbroek (2001), in the case of the unpolarized multi-level atom.

2. Model and Results

We used our new code to study the formation of the Stokes profiles of the Mg II h and k lines (respectively at 280.4 nm and 279.6 nm) in a homogeneously magnetized atmosphere. For zero magnetic field, we verified that the results of our code for the linear polarization of these lines agree with those presented by Belluzzi & Trujillo Bueno (2012, 2014).

Figure 1 shows a synthesis of the four Stokes profiles (intensity I , fractional linear polarization $q = Q/I$ and $u = U/I$, fractional circular polarization $v = V/I$) of the Mg II h–k doublet formed in a *uniformly magnetized* chromosphere, observed on-disk for values of $\mu = 0.1, 0.3, 0.5, 0.8$ (respectively, black, red, blue, and green curves). We used the FAL-C atmospheric model (Fontenla et al. 1993), according to which these lines form in a layer spanning approximately between 200 km (far wings) to 2200 km (line core) above the photosphere. For the magnetic modeling, we assumed a field with strength $B = 20$ G, inclined 30° from the local vertical, and with its projection on the plane of the sky pointing radially toward the solar limb (i.e., $\varphi_B = 180^\circ$). We note that the field strength of 20 G corresponds approximately to the critical Hanle field for the Mg II k line (Belluzzi & Trujillo Bueno 2011). We also note that for $\mu = 0.5$ (blue curve) the field is perfectly transversal to the line-of-sight (LOS), a condition that causes Stokes V to vanish.

The left panels of Figure 1 show the line cores and the region between the two lines with increased spectral details. We see how the core of the k-line Stokes Q and U in the magnetic case is affected by the presence of the weak magnetic field through the Hanle effect, showing a depolarization of the Stokes Q signal (with respect to the case of zero magnetic field, shown here only for the case of $\mu = 0.1$; see black dashed curves) and the corresponding appearance of a signal in the core of Stokes U . *In an optically thin plasma, and in the CRD limit, these would be the only observable effects in the linear polarization profiles of this line.* Because the h-line is intrinsically unpolarizable by radiation anisotropy (being a $1/2$ – $1/2$ transition; Casini et al. 2002), no linear polarization is detected in its core, since the ambient magnetic field is too weak to produce any significant Zeeman-effect signal. For the same reason, being the Larmor frequency much smaller than the fine-structure separation of the upper term, there are also no detectable effects of *atomic*

orientation (i.e., the magnetically induced population imbalance between atomic states of the form $(J, \pm M)$; Kemp, Macek, & Nehring 1984) in the circular polarization of the two lines.

The inclusion of PRD effects in the modeling is essential in order to produce the broadband linear polarization structure of the Mg II h–k doublet, as already demonstrated by Belluzzi & Trujillo Bueno (2012) for Stokes Q in the non-magnetic case. In particular, this polarization structure reveals the presence of quantum interferences between the $J = 1/2$ and $J = 3/2$ states of the upper term of the doublet. A striking result of our modeling is the fact that a corresponding broadband linear polarization manifests also in Stokes U (see, e.g., Figure 1), in the presence of a magnetic field, rather than only in the core as one would have expected based on the Hanle-effect mechanism.

An in-depth analysis of the line formation problem demonstrates that the appearance of this polarization in the broad wings of Stokes- U is mainly caused by the manifestation of magneto-optical (M-O) effects in the optically thick chromosphere. These effects are able to transform the broadband polarization that is observed in Stokes Q (even in the absence of a magnetic field) into detectable levels of Stokes- U polarization, already for magnetic fields of only a few gauss. Our analysis has also showed that a smaller broadband modulation of the Stokes- U polarization signal is additionally produced by the breaking of the cylindrical symmetry of the scattered radiation, as this is transported across the optically thick and magnetized plasma, despite the restriction of the model to a plane-parallel atmosphere, and even when M-O effects are neglected. This is demonstrated by the case of $\mu = 0.5$ (blue curve), where the magnetic field becomes exactly perpendicular to the LOS, thus making the M-O element responsible for the $Q \rightarrow U$ transfer identically zero.

Figure 2 reproduces the previous results in the case of a magnetic field with $B = 100$ G and the same geometry as before. We must note that, for this field strength, the Hanle effect of the k-line is practically saturated. The figure shows how the larger magnetic strength affects the amplitude and separation of the polarization lobes observed in the broadband structure of Stokes Q and U outside of the h–k spectral range. This is clearly a M-O effect, since the associated dispersion profile is sensitive to the Zeeman splitting of the atomic levels induced by the presence of the ambient magnetic field. In the core of Stokes Q and U , instead, the changes are dominated by the depolarization of the signal in the saturation regime of the Hanle effect. Stokes V is evidently dominated by the longitudinal Zeeman effect, and so its amplitude scales linearly with the magnetic strength.

An analysis of the Stokes- U contribution to the source term in the RT equation as a function of height reveals that these M-O effects in the very far wings of the h–k doublet occur in the upper photosphere, at a height of $\sim 200 - 500$ km in the FAL-C model atmosphere adopted for these simulations. This is true also for the spectral region between the two lines. The line core polarization is instead produced in the low transition region (above ~ 2000 km).

The top and center panels of Figure 3 show the details of Stokes V/I in the spectral range around the Mg II k-line, for the models of Figures 1 and 2, respectively, and in the case of $\mu = 0.8$ (black solid curve). Overplotted with the gray dashed-dotted curve is the *weak-field approximation*

of the circular-polarization profile. For our model atmosphere with a uniform magnetic field, this turns out to be proportional to the first derivative of Stokes I with respect to wavelength, the so-called *magnetograph formula* (e.g., Landi Degl’Innocenti & Landolfi 2004). For comparison, the bottom panel shows the intensity profile of the k-line (black solid curve). Overplotted with the gray curve is the same profile in the CRD limit.

We note how the weak-field approximation fails to quantitatively reproduce the secondary lobes of the Stokes- V profile. These are formed in the outer wings of the characteristic peaks of the Mg II k intensity profile, and are therefore sensible to the presence of PRD effects in the line forming region (see bottom panel). Conversely, the magnetograph formula appears to work extremely well over a spectral region that extends from the line center out to peaks of the intensity profile, where the CRD approximation to the line formation is applicable. With this restriction, our results indicate that the magnetograph formula retains its diagnostic value, even in complex atmospheric scenarios as the one described by our model.

An analysis of the contribution function for Stokes V shows that the secondary lobes are formed in the chromosphere proper (between approximately 1000 and 2000 km). Hence, *the magnetograph formula applied to the Mg II h-k doublet provides a valuable quick-look magnetic diagnostics of the low transition region, whereas it may significantly underestimate the strength of chromospheric fields.*

In particular, the inverted values for the LOS strength reported in Figure 3 were estimated by applying the magnetograph formula in a spectral range where the fractional circular polarization is larger than 0.04% (0.2%) for the case of $B = 20$ G (100 G). In that restricted region, the relative error on the inverted field strength caused by the weak-field approximation is only a few percent.

We must also point out that, for a given optical depth, observations closer to disk center (i.e., for larger values of μ) probe larger geometric depths in the atmosphere, and so we can expect that the error in the application of the magnetograph formula would increase in the presence of magnetic-field gradients along the atmospheric height. On the other hand, the validity of the weak-field approximation in the CRD spectral region of these lines must remain true *at each height* of the atmospheric model, potentially offering a computationally economic tool for the forward modeling of Stokes V in the presence of atmospheric gradients. This conclusion is supported by previous findings about the applicability of bisector methods to infer the height dependence of the magnetic field in chromospheric lines (e.g., Uitenbroek 2003; Wöger et al. 2010).

3. Conclusions

The following conclusions can be drawn from the above results. First of all, the importance of PRD effects for the formation of the linear polarization profiles of the Mg II h and k lines (Auer, Rees, & Stenflo 1980; Henze & Stenflo 1987; Belluzzi & Trujillo Bueno 2012, 2014) is confirmed by these new calculations in the presence of a magnetic field.

Secondly, M-O effects are found to be responsible for the appearance of important levels of *broadband* Stokes- U polarization. This result contrasts the common belief that magnetic fields produce significant polarization only in the line core, and in particular that the manifestation of M-O effects requires the presence of strong magnetic fields (e.g., Skumanich & Lites 1987). The fact that M-O effects are so outstanding in the polarization profiles of the Mg II h–k lines is due to the peculiar combination of a strong opacity in the far wings and a significant level of scattering polarization ($\sim 2\%$; see Figure 1) induced by radiation anisotropy, which are produced in the adopted atmospheric model.

In our two-term model atom, these M-O effects induce the appearance of a polarization signal that encompasses the entire spectral range of the h–k doublet (spanning several nm; see Figures 1 and 2), and which is dominated by the signature of quantum interferences in the upper term of the Mg II atomic model.

A very remarkable result is the manifestation of these polarization transfer effects already for relatively weak fields—in the modeled case of the Mg II h and k lines, for field strengths of only a few gauss. This opens a completely new diagnostic window for the magnetism of the quiet-Sun upper atmosphere, since these effects should be detectable also in other notable chromospheric lines, such as the Ca II H–K doublet around 395 nm, the Na I D-doublet around 590 nm, and the H I H α line at 653 nm.

In the context of this work, the presence of broadband signals in the Stokes Q and U polarizations of the Mg II h–k doublet make this line set a very attractive and potentially powerful diagnostic for synoptic magnetic studies of the solar chromosphere and upper photosphere. The relatively large amplitude of the signals over a spectral range spanning many Doppler widths should facilitate the design of high-throughput and fast cadence imaging polarimeters, which could rely on relatively low polarimetric sensitivity and spectral resolution, at least for the diagnosis of the upper photosphere and lower chromosphere, where these broadband signatures are produced. The inner cores of the k and h lines, where the signatures of the Hanle and Zeeman effects dominate the polarization signal, probe instead the low transition region (above ~ 2000 km in the FAL-C model). Hence, *the broadband Stokes profiles of the Mg II h and k lines offer an opportunity to study simultaneously the magnetic structure at the base and the top of the chromosphere.*

Our simulations show that the amplitude of the Hanle-effect polarization in the core of the Mg II k-line can be as large as $\sim 1\%$, and therefore relatively easy to detect using narrowband ($\sim 0.25\text{\AA}$) filter polarimeters. In fact, a systematic study of the variation of narrowband-integrated Stokes Q and U polarizations as a function of the vector magnetic field should be conducted in order to assess the feasibility of filter-based, full-disk polarimeters for the Mg II h–k doublet.

Finally, *the magnetograph formula applied to the Stokes V profiles of the Mg II h–k doublet retains its diagnostic value as a proxy of the magnetism of the low transition region*, although our modeling also shows that its applicability breaks down when PRD effects in the line formation region become important. This conclusion reinforces the relevance of these lines for the diagnosis

of chromospheric magnetic fields, and in particular it provides a direct and inexpensive tool for the quick-look inversion of large spectro-polarimetric datasets of chromospheric lines, providing additional evidence to the importance and feasibility of full-disk observations of the solar chromosphere at these wavelengths.

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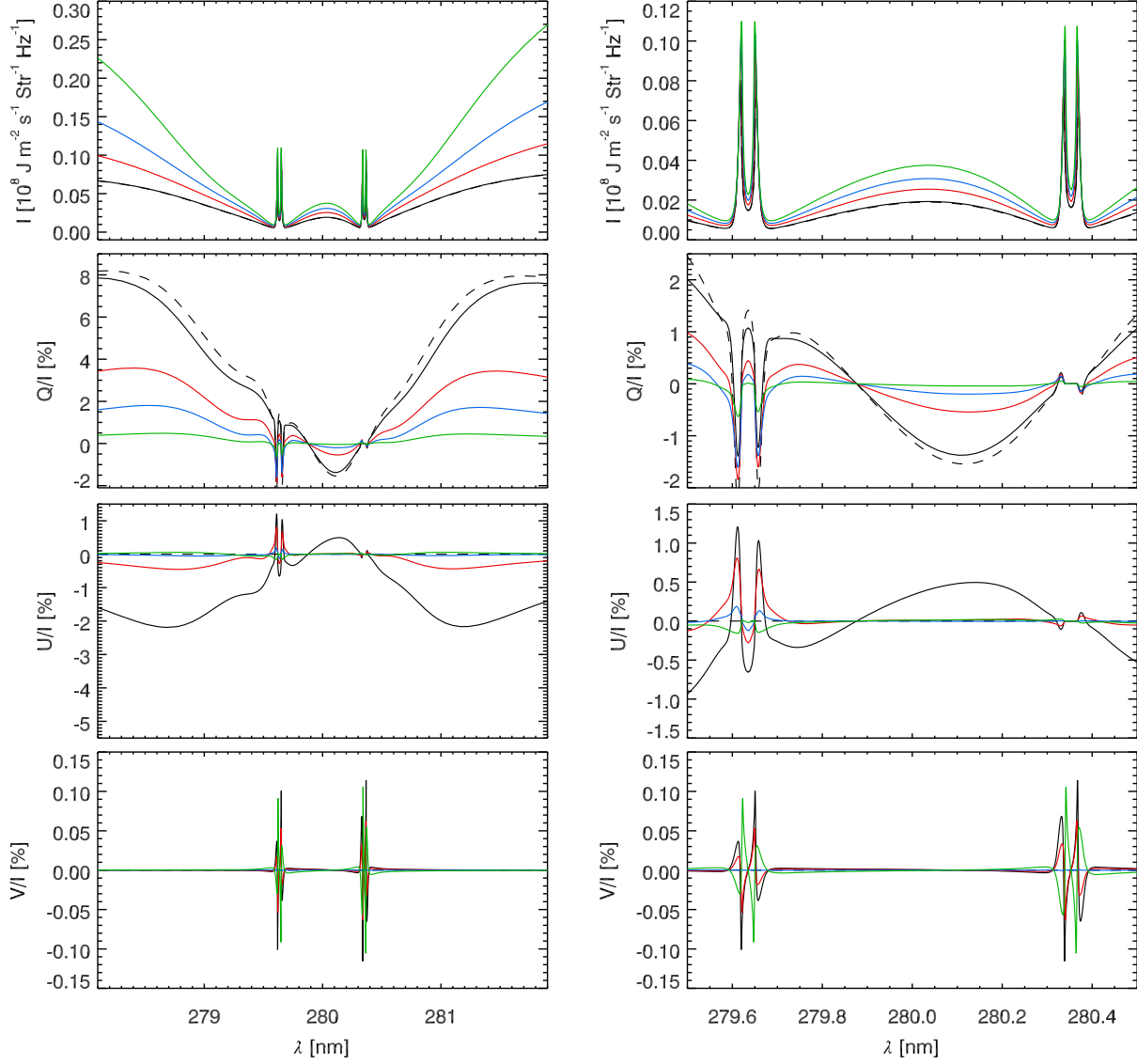


Fig. 1.— Stokes profiles of the Mg II h–k doublet modeled in a weakly magnetized FAL-C atmosphere ($B = 20$ G, $\vartheta_B = 30^\circ$, $\varphi_B = 180^\circ$) and for various directions of the LOS (corresponding to $\mu = 0.1, 0.3, 0.5, 0.8$, respectively, for the black, red, blue, and green curves). The dashed curves correspond to the Stokes profiles for the non-magnetic case and $\mu = 0.1$. *Left*: note the remarkable presence of broadband Stokes- U polarization due to the combination of upper-term quantum interferences and magneto-optical effects. *Right*: finer details of the polarization of the h and k line cores and of the quantum interference pattern between them. We note in particular the reversal of the sign of Stokes V (and more subtly, of Stokes U) for $\mu = 0.8$, in accordance with the sign of the LOS projection of the magnetic field vector. We also note the complete absence of a magnetic signature in the core of the h-line at 280.35 nm, as expected for an intrinsically non-polarizable transition in the weak-field limit.

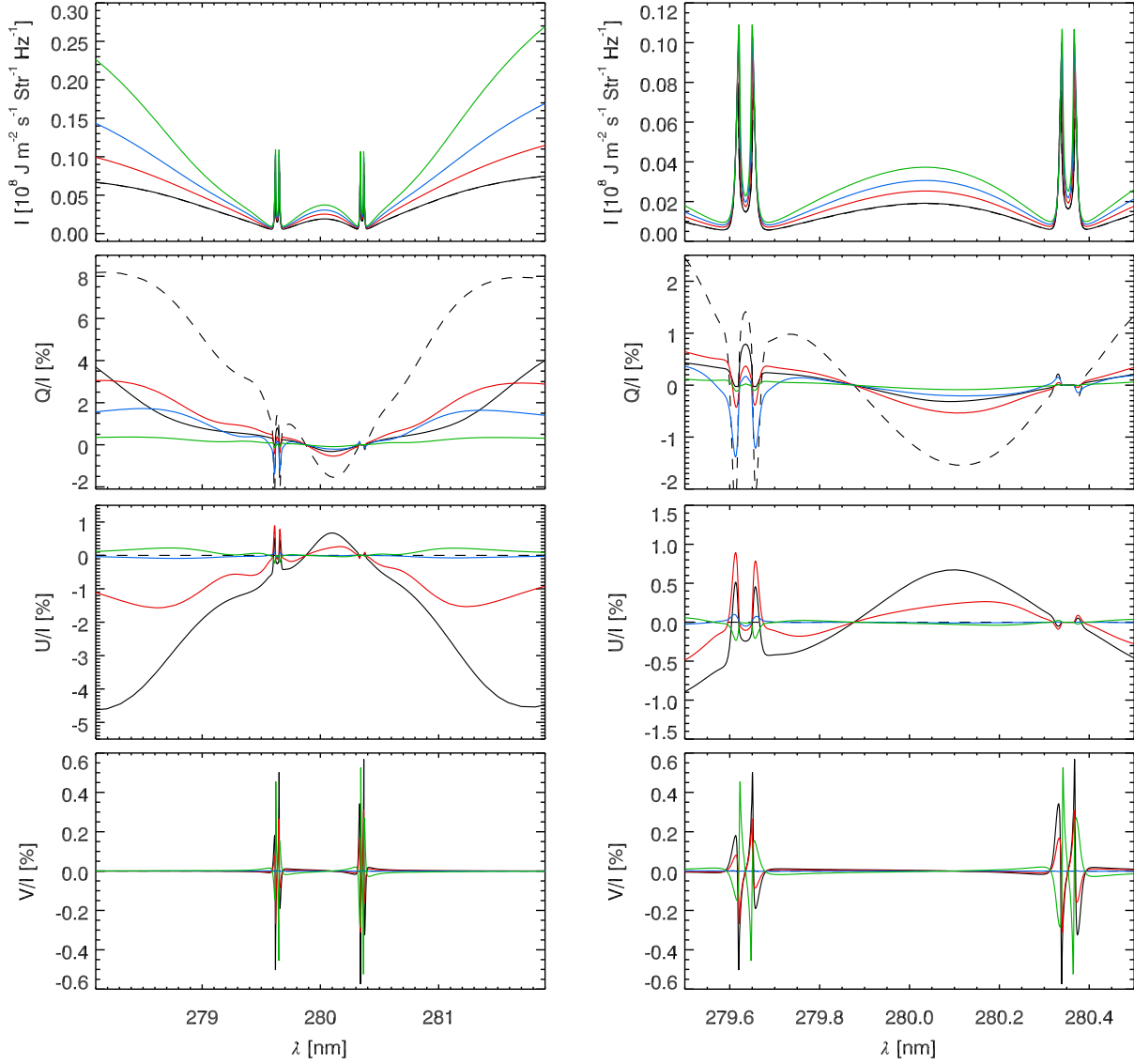


Fig. 2.— Same as Figure 1, but for a magnetic field strength $B = 100$ G. We note how the separation of the lobes in the broadband polarization structure of Stokes Q and U increases with the magnetic strength because of the M-O effects. The changes in the line cores are instead dominated by the depolarization associated with the larger field strength.

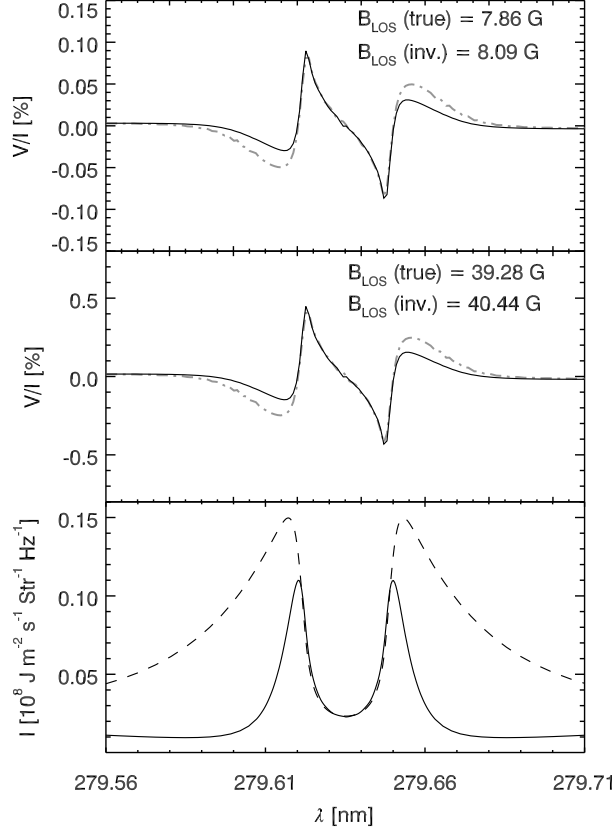


Fig. 3.— Fractional circular-polarization profiles $v = V/I$ of the Mg II k-line, for the magnetic models of Figure 1 (top) and Figure 2 (center), and corresponding intensity profiles (bottom) for the CRD (dashed) and PRD (solid) regimes. Only the case of $\mu = 0.8$ is shown here (cf. green curves of Figures 1 and 2), showing the fully resolved line core and the near wings of the line. The dashed-dotted curves show the weak-field approximation to Stokes V (magnetograph formula). We note the extremely good fit of this approximation in the spectral region where the line formation is dominated by the CRD regime. The reported values of the inverted LOS field component were estimated by restricting the use of the magnetograph formula to the inner lobes of the k-line, where the v fractional polarization is larger than 0.04% and 0.2%, respectively, for the 20 G and 100 G field strengths.